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ORIGINAL ARTICLE

Automated fenestration allocation as complying with LEED rating system

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Abstract During the last decade, environmental issues in the design have started to attack architecture to preserve natural resources, and to improve the performance of designs. Many validation rating systems for sustainability are used to check the compromise of specific buildings with energy consumption and environmental issues. One of the great problems facing architects is checking that their designs compromise with the various rating systems. On the other hand, new techniques in architectural design based on automation, parametricity and algorithms have invaded the design with complicated methods and applications.

One of the main environmental obstacles facing any design is the allocation of fenestration, which used to be linked mainly to the design of the facade. Contemporary windows allocation in design has started to be a more complicated issue when related to complying with certain validation environmental rating systems such as LEED. Through the use of common design strategies based on the contemporary techniques in architectural design, this issue could be achieved automatically.

The allocation of windows, through the help of certain well known heuristic algorithms and simulation programs, could be reached automatically to compromise with the LEED rating system by achieving the required daylight amounts with a minimum solar radiation inside a particular building. This research shows a design method based on simulation techniques with the help of heuristic algorithms through a parametric design that automatically allocate windows to comply with LEED. At the end of the research, a small project is discussed for evaluating the design process.

1. Introduction

Appropriate fenestration allocation is an important issue in architecture design since it is not only related to the design of facades, but is also crucial in improving the indoor environmental quality.

Improving daylight inside a particular area is related to the suitable allocation of windows in the space. Nevertheless the allocation of these windows that improves daylight could add another point, that is, the thermal loads. These thermal loads could add additional power loads to the building. The improvement of daylight to a certain limit required in an area, with the minimum added thermal loads is a great demand in

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contemporary architectural designs. This issue could be evaluated by detecting the design to compromise with the known LEED rating system that shows particular needed daylight values with the minimum thermal loads. In order to achieve the optimum fenestration allocation for a particular facade that fulfills the previous rules, new design methodology will be discussed. This methodology is based upon the parametric design, the LEED rating system credits for daylighting and energy, simulation software, and heuristic algorithms.

This methodology aims automatically at allocating optimum openings location which compromise with the LEED rating system through the integration of the previously discussed four issues.

2. Main issues forming the design methodology

2.1. LEED rating system (concerning daylight)

Leadership in Energy and Environmental Design is a rating system for the design of green buildings which helps to measure the environmental issues of any design. The LEED [1] rating system is divided into seven main parts for any design: Sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design, and regional priority. The allocation of windows in a project will undoubtedly affect the daylight and thermal loads accompanying it.

The checklists related to daylight and energy compromising with LEED are found in the parts of energy and atmosphere, and indoor environmental quality.

2.1.1. Energy and atmosphere

This part of checklist consists of three prerequisites and six credits, the second prerequisite and the first credit are the only items related to fenestration allocation with its thermal loads.

- *Prerequisite 2: Minimum Energy Performance*: The intent of this prerequisite is to achieve the minimum level of energy needed for the proposed design to be environmentally-friendly.
- *Credit 1: Optimize Energy Performance*: This credit is similar to the previous one, but it aims to increase the energy performance beyond the prerequisite. According to the amount of improving the energy performance, more credits will be achieved.

2.1.2. Indoor environmental quality

This part checklist consists of eight credits, the last credit mainly concerns daylight which is;

Credit 8.1: Daylight and Views: Daylight. The intent of this credit is to connect between the indoor spaces and the outdoor atmosphere through the introduction of daylight, and views into 75% from the regularly used zones through one of the following four options;

- Computer simulation should be used to check that 75% of all the main occupied areas achieve daylighting illumination levels not less than 25 footcandles, or more than 500 footcandles on 21st of September at 9 a.m and 3 p.m. (any areas less or more than the previously discussed values should be neglected).
- Prescriptive by using a combination of all daylighting sources to achieve the previous needed amounts, but based upon specific calculation rules.
- Measuring indoor daylight to achieve the same illumination levels stated as above in the first option. Measurements should be taken on 10-foot grid for all central zones and recorded on the floor plans.
- A combination between any of the above options to document the minimum daylight in at least 75% of central usable spaces. All the options used for each space should be shown clearly on building plans.

Since the applied design process is an automation of designing openings, the method for examining the daylight credit will be based on the first one, which is the computer simulation.

2.2. Simulation software

Daylight and solar radiation simulation are methods for using computer software to predict the performance of the current design [2]. Through the use of computer software, the new programs are capable of providing a full report on daylighting, and solar radiation within any space, any sky, and at any specific time.

Software like Lightscape, Desktop Radiance, Lumen, Micro, Ecotect and Dialux could generate an analysis grid showing the amount of daylight and solar radiation in any space, which could be used to examine the performance of a particular design (Fig. 1) [3].

2.3. Parametric design

A parametric design is creating a form based on certain variables, by changing these variables new forms are generated. The windows allocation and dimensions could be created through parametrical relations to be able to achieve the LEED credits. This part is important in automating the design of fenestration for facades. The fenestration position and dimensions should be defined parametrically for each facade, to be able to generate variations in the designs, related to certain inputs [4].

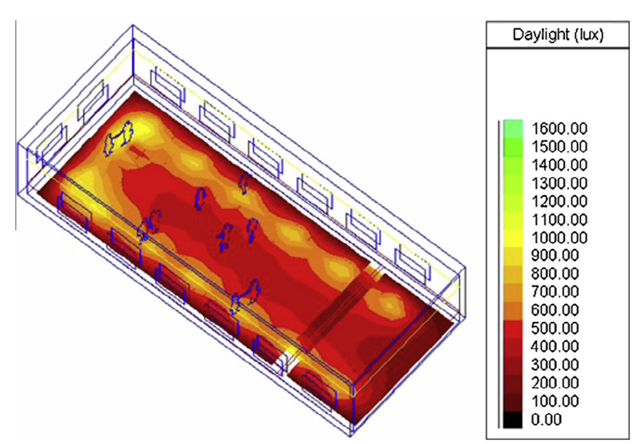

Figure 1 Daylight grid analysis generated from a simulation program.

The main idea is to analyze the facade and break it down into variables and values by translating the facade with its openings into pure geometry, points, lines, and planes. Each of the previous items of the façade can be defined as a variable in space or relative to other things in the facade.

2.3.1. Parametric design concept

For example, the simplest way to create the square plane in the following figure is to break it down into its simplest elements, which are the four corner points. A parametrically defined square has four points determined as parameters (or variables) in Cartesian space through the coordinate system (x, y, z). The plane is formed from the four main points, the first point A could be fixed (not variable) at coordinates $(0, 0, 0)$, the other three points could be defined in forms of $b(x_b, y_b, z_b)$, $c(x_c, y_c, z_c)$, $d(x_d, y_d, z_d)$. It is clear that by changing the values of the previous variables an infinite number of planes could be created. The parameters here are the values of x_b, x_c, x_d, y_b, y_c, y_d, z_b, z_c, z_d, and the variations in these values could generate an infinite number of planes. The process of changing variables could be repeated until the proper plane is created. The same idea could be applied to generate other geometrical forms (Fig. 2).

To create objects parametrically on a certain plane there are two methods; the first one (complicated) is the use of world coordinate system (X, Y, Z) to determine the position of the points and the second one which is the more usable in the parametric design, is to relate the points to the surface of the plane and define the coordinates of these points as (U, V) values, where the u and v are the distance between the points and a reference point on the plane (in this method there is no need for the z-coordinate) [5].

Based on the second common method it is easy to create any surface, generate the parametric coordinates system on the new surface, and then determine the position of these points on the surface based on the new system (U, V) without the need to the Z coordinate. (since the u and v coordinates are related to the new surface) (Fig. 3).

Through the use of the previous second method concept, the position of the windows on any surface (façade) can be determined parametrically.

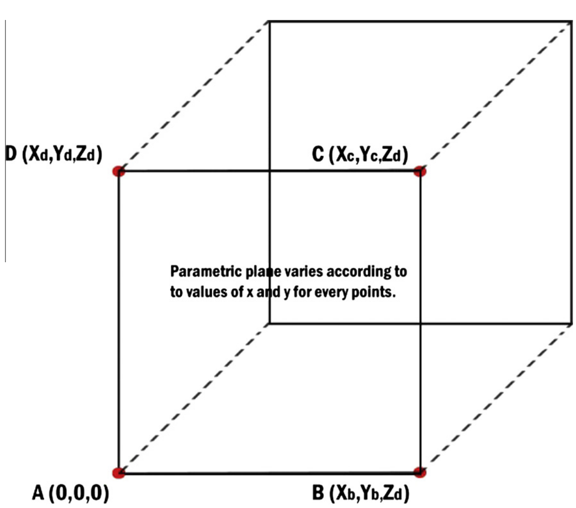

Figure 2 Generating a square plane parametrically.

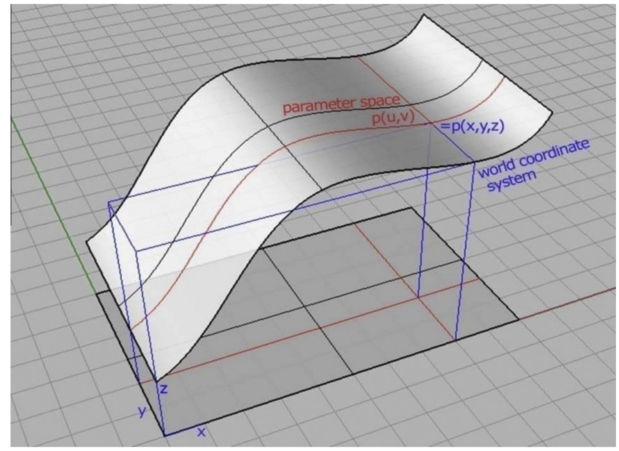

Figure 3 Equivalent of the point $P = (U, V)$ on the world coordinate system $p = (X, Y, Z)$.

2.4. Heuristic algorithms

An algorithm is the process of solving a problem in limited steps. The algorithms start to be complicated when studying their types in computer science. Heuristic term is usually used with algorithms that try to find the optimum solution among all possible (solutions) parameters. Sometimes these solutions are not that accurate to be the optimum that's why it is still called heuristic, until it is proven to be the best solution.

The most common heuristic algorithms used in architectural applications are genetic algorithms and simulated annealing algorithms. These two algorithms try to find the optimum solution (the solution in the design process case is the group of parameters that solve the design problem). Before discussing the difference between the two algorithms, at first these algorithms will be explained.

2.4.1. Genetic algorithms

This heuristic search optimization method is based on simulating biological evolution through the mutation of characters between successive populations, in generating an optimized solution [6] (Fig. 4).

In a GA there is only one optimum solution for the problem, while the group solutions are available in each population. Each new population is called a generation. Every solution in each generation is presented with a binary string (reflects the characteristics of this solution), this string is usually called a chromosome [7].

The chromosome of every solution consists of alleles determined as the binary code bits, this binary code reflects the parameters previously explained for every solution for the problem. In each new offspring the alleles are changed (called crossover step) between different chromosomes to generate new optimized solutions (Fig. 5).

A simple genetic algorithm can be summarized in the following steps;

– The GA starts with a group of solutions each are of random alleles.
– The iteration process starts after assigning every solution a fitness function, showing the performance value for each solution.

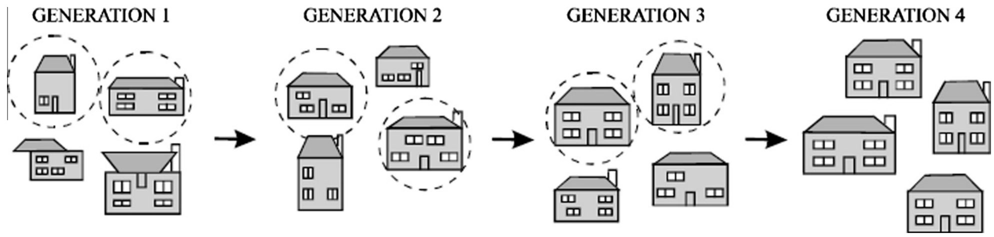

Figure 4 Optimization of design through evolving successive populations.

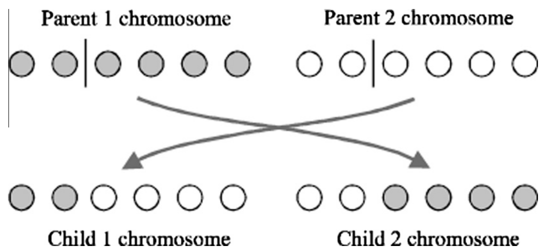

Figure 5 The behavior of the crossover operator. The vertical line shows the position of the random crossover point.

- Based on the fitness function for every solution, these solutions are placed in temporary pool organized according to their performance.
- Two parents (solutions) are then randomly picked from this area to start producing a new generation.
- Offspring are generated by the use of the crossover operator, which randomly allocates genes from each parent's genotype to each offspring's genotype.

This entire process of evaluation and reproduction then continues until, either a satisfactory solution emerges or the GA will run for more generations.

2.4.2. Simulated annealing

One of the most important methods applied in finding the optimum solution of the problem is the simulated annealing which is based on the process of annealing [8]. Annealing is well known as a metallurgical process. It is based on cooling a certain metal, then heating and cooling it slightly, this slowly cooling fixes the new metal with its new atomic structure.

In the simulation of this annealing, variation is kept in temperature as a simulation of the annealing process. At first, the temperature is high and then it is cooled slowly when the algorithm runs. While increasing the temperature of the metal again, the algorithm will accept worse solutions. This acceptance helps the algorithm to search in new zones to reach more minimum temperature than the previous one. The previous steps allow the algorithm to focus gradually in most of the areas while reducing the temperature till a solution close to the optimum solution can be found (Fig. 6).

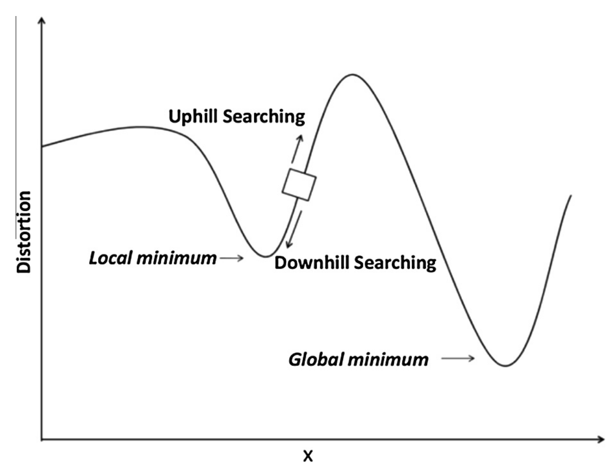

Figure 6 Increasing and decreasing temperature to search for an optimum solution.

Table 1 A comparison between a Genetic algorithm and simulated annealing.

	Memory	Growth	Variation	Region
GA	– Need particular amount of memory – Explicit – Elitism – Implicit-keeps track of high-performance building blocks; sequence of generations, propagates useful genetic information	– Unsystematic manner – Based on small changes in the existing solution based on its region	– New solution spaces due to the combinations of already existing solutions – GA has enormous variations by starting new random populations of solutions	– No clear definition for neighborhood – Through the crossover between solutions new solutions are generated
SA	– Almost no use of memory – It is used only to restart the search after each temperature reduction	– Searching is minor as it progresses, with lower chances of accepting different solutions from the current one	– At the early stages of search chances of accepting solutions that significantly decrease performance is higher, meaning that new regions of the search space are explored	– Identification of the neighborhood should be clear – Not the entire neighborhood is important that is why its size is not important

The most common terms in any simulated annealing algorithm are local and global minima and maxima, which describe the highest and lowest values of a specific function which is either local or global. The main aim for any simulated annealing is to find the global value and not the local one.

The algorithm of any simulated annealing can be explained simply through the following steps:

- Get an initial state with energy x.
- Make an initial state the current state.
- Select an initial high temperature "T".
- While the system is not "frozen yet".
- begin, pick a random nearby state with energy x_p.
- let $\Delta x = x_p – x$
- if $\Delta x \leqslant 0$ then, the new state becomes the current state.
- Else
- Reject state.
- End
- "reduce the temperature T by ΔT
- Output the current state.
- End.

2.4.3. Comparison

The following table shows a comparison between a Genetic Algorithm and a simulated annealing algorithm as a help in selection of the suitable algorithm (see Table 1).

3. Automated fenestration allocation methodology

The following diagram (Fig. 7) summarizes the design methodology for the automated fenestration allocation.

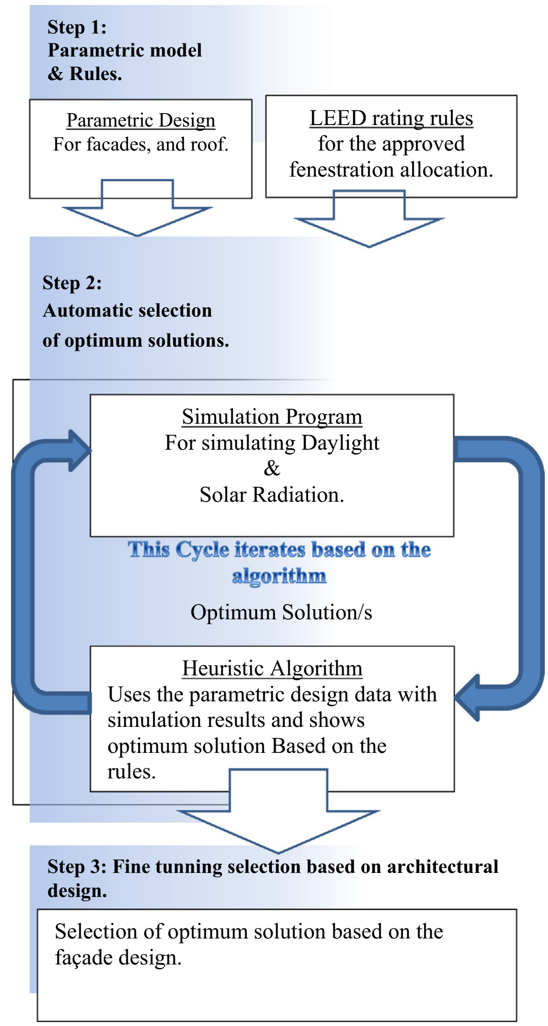

Figure 7 Main steps of the design methodology.

3.1. Step 1: parametric model and rules

3.1.1. Parametric design of facades and roof (in case of presence of skylight)

This step is mainly concerned with designing the facade parametrically similar to the previously explained method. The plane representing the facade and the windows locations should be determined based on points on the surface of the facade through the use of (u, v) coordinates system (Fig. 8). This process prepares the positions of windows based on variables or parameters in the form of u and v on plane representing the facade. The u and v variables later on will be governed automatically through the algorithms previously discussed to start generating the permutations based on the results of simulations of daylight and solar radiation. The previously discussed method is the simplest form, and other forms could be applied based on the different designs of the facades.

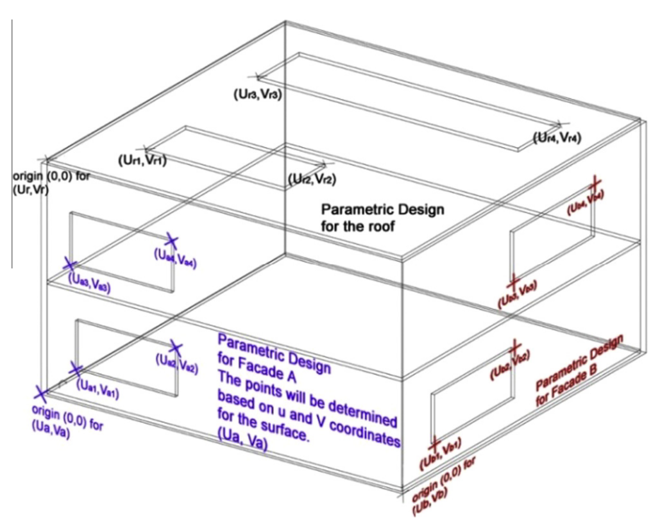

Figure 8 A simple example for determining the openings for facades and roof parametrically.

3.1.2. LEED rating rules for the approved fenestration allocation

Based on the LEED rating system the rule governing the selection of solutions, will be based on the previously discussed credits for the LEED rating system, which are the minimum energy due to solar radiation and credit 8.1 of daylighting in the indoor environmental quality.

These rules will be used by the heuristic algorithm to examine (based on simulation) the amounts of solar radiation, and daylighting in a certain space such that 75% of the spaces are not less than 25 footcandles, or more than 500 footcandles on 21st of September at 9 a.m and 3 p.m. At first, the rule of daylighting should be fulfilled, and then all the accepted solutions will be compared to select the solutions with the lowest solar radiation.

3.2. Step 2: automatic selection of the optimum solution/s

3.2.1. Simulation program for simulating daylight and solar radiation

Using simulation software for the daylight and solar radiation, the software starts to simulate the performance of spaces based on the parametrically designed facades. The software generates two grids, one for the values of daylight and the other for solar radiations, the values generated from these grids will be supplied to the optimization algorithm which examines the results of the simulations.

3.2.2. Applying heuristic algorithm

In this step, the architect determines the suitable optimization algorithm whether it is the genetic or the simulated annealing one. The heuristic algorithm will manage the flow of parameters, and performance between the simulation and the modeling software. The algorithm takes the parameters of the openings with their performance from the simulation program. Then based on the rule governing the selection of the optimum solution (parameters), the algorithm starts sending new parameters to the simulation program and receives the results. The previous steps are iterated till the optimum solution is reached.

3.3. Step 3: fine tuning selection based on architectural design

This step is the final step; it is after the heuristic algorithm generates a group of optimum solutions for the fenestration allocation. Usually these algorithms generate a group of solutions with nearly similar performance.

The architect can examine these solutions from the architectural point of view for the design of the façade, and then select the most suitable one.

4. Application

The following application is a multipurpose building in Cairo with dimensions of 12×12 m and a height of 4 m. It consists of three facades of merging between curtain walls and solid panels, and the fourth facade is a solid one in the south direction. The building roof is a skylight roof with pyramid-like panels.

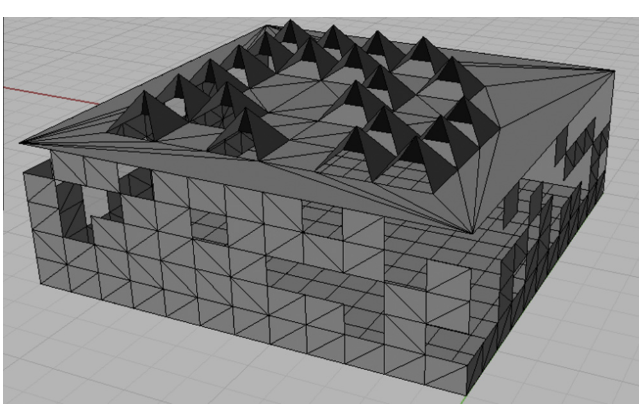

Figure 9 Main form of the multipurpose hall, with the fenestrations and the skylight determined parametrically.

The previously discussed steps (methodology) will be applied to automatically design the three curtain wall facades, and also to determine the number and allocation of skylight units to reach the needed daylight amounts with minimum solar radiation according to LEED rating system. The application will be based on the use of the graphical algorithm tool known as Grasshopper, with other applications such as the Geco that transforms data to the Ecotect program for simulation and the Galapagos tool for optimization based on SA or GA.

The design passes through the following steps (according to design methodology).

4.1. Step 1: parametric model and rules

4.1.1. Parametric design of facades and roof (in case of presence of skylight)

The building facades and skylight are generated parametrically to let the optimization algorithm manage the process of optimization according to results of the simulation software.

Each facade is divided into curtain wall panels, and these panels can be replaced with solid panels parametrically, through the change of specific variables. Also, the skylight was designed parametrically to determine the location and the number of skylight units in the roof (Fig. 9).

4.1.2. LEED rating rules for the approved fenestration allocation

The data generated from the simulation software for daylight are examined according to the daylight LEED rules. Then all the solutions which do not fulfill the rules will be neglected. Other solutions will continue to be simulated according to the solar radiation. As shown in the following figure (Fig. 10) the solutions are examined to be either true or false according to fulfilling the daylighting rule.

4.2. Step 2: automatic selection of optimum solution/s

4.2.1. Simulation program for or simulating daylight and solar radiation

Through the use of Geco plugin under Grasshopper the parameters with their generated models are exported to the simulation program Ecotect to simulate the performance (daylight and solar radiation) for each of the exported parameters, to be examined through the previously discussed rule (Figs. 11 and 12).

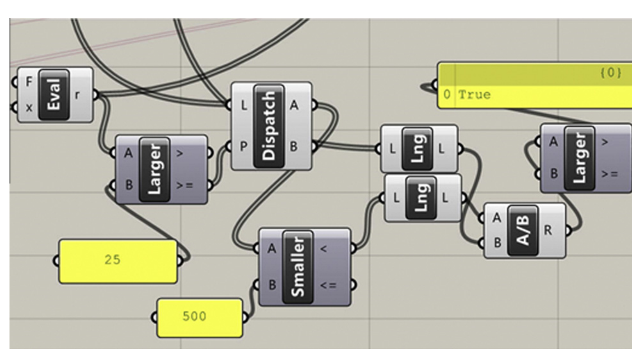

Figure 10 All the solutions that compromise with the LEED rules are accepted, and other solutions are neglected.

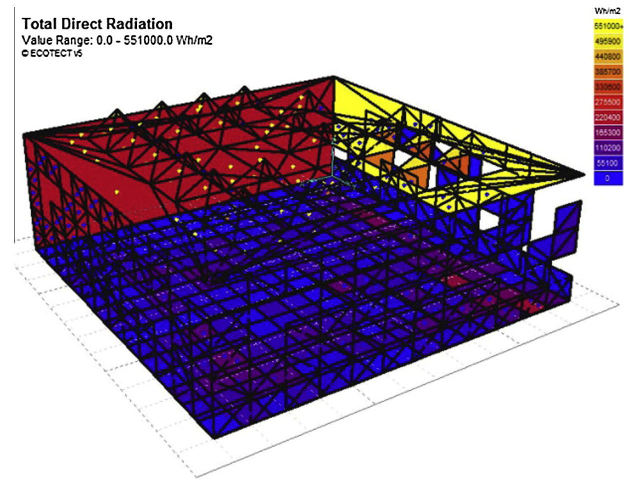

Figure 11 Grid analysis by Ecotect showing the solar radiation for the current design.

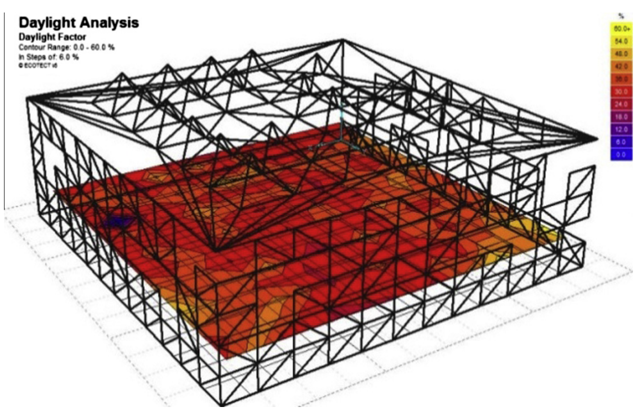

Figure 12 Grid analysis by Ecotect showing the daylight distribution for the current design.

4.2.2. Applying heuristic algorithm

In this application, the Galapagos tool based on the genetic algorithm is used to manage the flow of the geometric model with its parameters between the modeling program and Ecotect. Based on the previously discussed rule and comparing results of solar radiation of all the accepted solutions, the genetic algorithm starts generating offsprings and mutating between the solutions to reach the optimum solution. The genetic algorithm reaches the solution after iterating the previous steps in each offspring till it reaches the optimum solution.

After generating more than 40 generations (with a population of 10 for each) the minimum solar radiation starts to be nearly constant with the different offsprings (Figs. 13 and 14).

4.3. Step 3: fine tuning selection based on architectural design

In this step, the optimum group of solutions (population) are examined and compared architecturally, according to the design of the facades. The following figure shows the solutions with minimum solar radiation. The minimum four solutions are very close in their performance. So, the four solutions are compared architecturally and one of them is selected (Fig. 15).

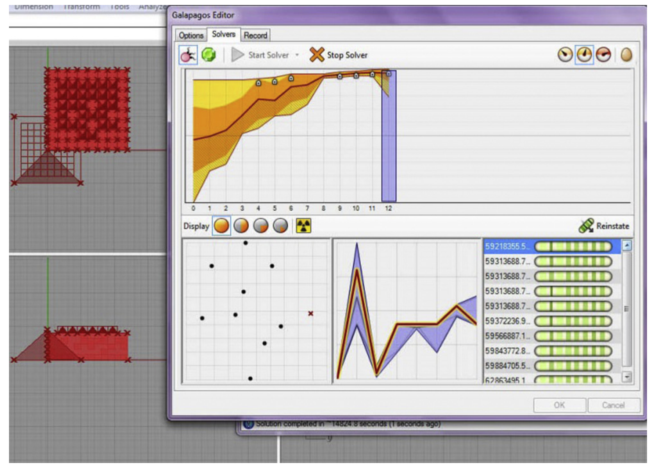

Figure 13 Galapagos interface is showing the different the generations created by a Genetic Algorithm.

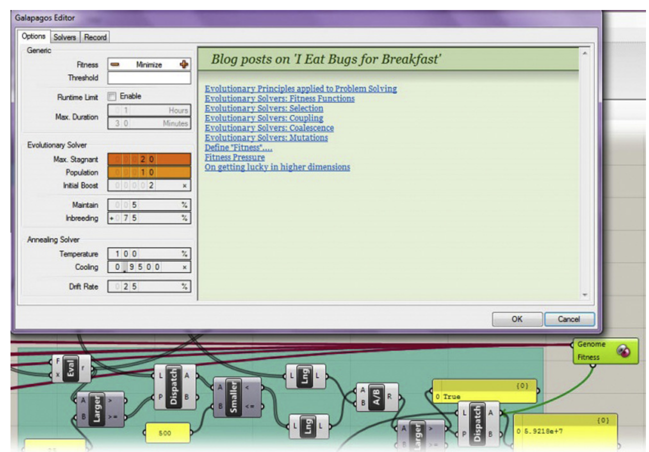

Figure 14 The number of populations per generation adjusted by Galapagos for the genetic algorithm.

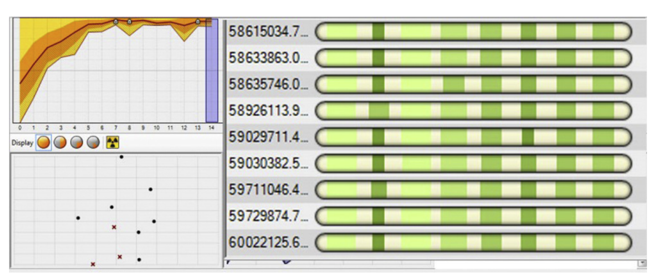

Figure 15 The optimum population results from the GA with minimum solar radiation and accepted amounts of daylight.

4.4. Results

The design starts with a random value for the parameters of fenestration, and skylight. Based on the previous discussed automated fenestration design methodology, the optimum fenestration allocation is automatically determined based on the accepted performance of daylight according to LEED

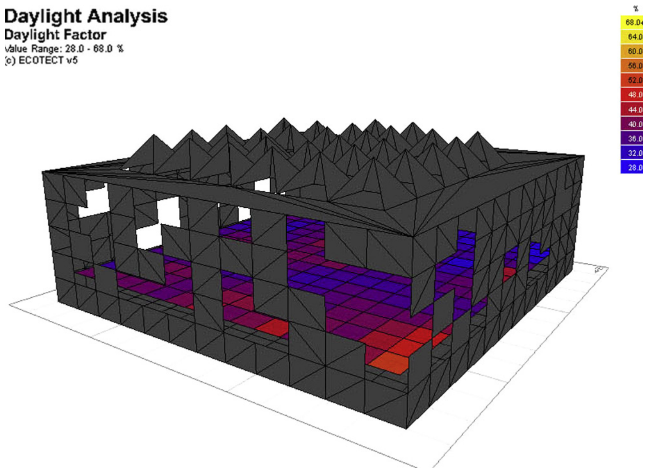

Figure 16 Final design with its daylighting simulation grid.

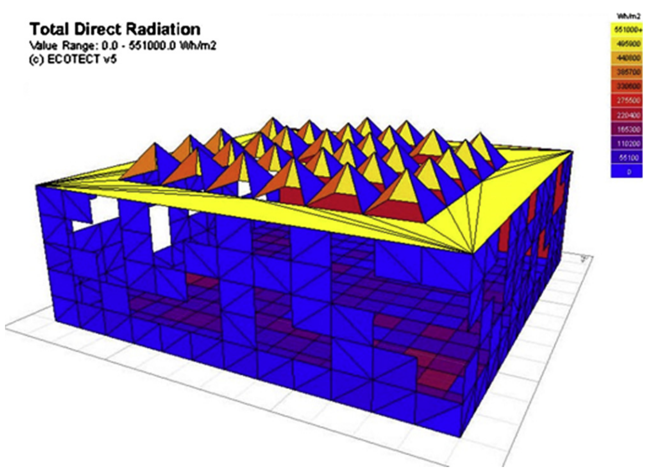

Figure 17 Final design with its solar radiation analysis Grid.

rating system and with the minimum total solar radiation loads. Through the design methodology the solar radiation loads from the fenestration allocation decreased from about 78 million W h/m^2 to 58.6 million W h/m^2, which is about 26% less than the total loads found in the initial parameters (Figs. 16 and 17).

5. Conclusion

Many of the contemporary architectural designs that need to comply with sustainability rating systems are based on certain computations or simulations. These simulations are crucial in examining the performance of a specific building to comply the different rating systems. Through the use of simulations programs, and algorithmic design methods the architectural design can not only be examined but can also be a way to search for the optimum solutions that can perfectly improve the performance of a building.

The automation of fenestration allocation as a comply with LEED could be achieved through a design methodology based on three main steps; the first one is creating the design parametrically and the LEED rules, the second step is the automatic selection of solutions through the intertwinement between simulation program and heuristic algorithm, and the last one is the selection of optimum solution to comply with the facade.

The automation of design to comply with LEED, based on the same idea could be progressed to include many items related to sustainability with the fenestration allocation, such as the roof inclination, building volume and shape, and others in one similar design methodology.

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